

**A NEW CATHODE-RAY OSCILLOGRAPH AND ITS
APPLICATION TO THE STUDY OF POWER LOSS
IN DIELECTRIC MATERIALS**

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A NEW CATHODE-RAY OSCILLOGRAPH AND ITS APPLICATION TO THE STUDY OF POWER LOSS IN DIELECTRIC MATERIALS ¹

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ABSTRACT

A cathode-ray oscillograph is described in which the electron beam, supplied from an incandescent filament, is accelerated in two stages. The beam is formed by a low-voltage accelerating field between the cathode and anode and after being deflected is further accelerated just before it reaches the fluorescent screen. In this way a very bright fluorescent spot is obtained without sacrificing sensitivity. With a cathode-anode voltage of 500 volts and a fluorescent-screen voltage of 5,000 volts the electrostatic sensitivity is 3 mm per volt and there is no difficulty in obtaining instantaneous photographs of 60~ phenomena. A method using the oscillograph for measuring power factor of a dielectric material from a single cycle of alternating stress is developed and analyzed. While this method does not give as precise values as a balanced bridge method of measurement, it may be used to make a continuous record of power loss in a dielectric material for individual cycles of stress at commercial frequencies. It should be useful in studying the phenomena which accompany the electrical failure of the material. It is equally applicable to very large or very small specimens. The limitations and precision of the method are discussed in some detail.

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I. INTRODUCTION

When a dielectric material is subjected to an alternating electrical stress some energy is absorbed and transformed into heat. The power loss is usually very small and special bridge methods and wattmeter methods have been devised for its measurement. These methods require that the power loss be constant during the time required to balance the bridge or read the wattmeter, a minimum of some seconds.

If the dielectric material is in an unstable state and the power loss is changing rapidly the methods ordinarily used for its measurement are inapplicable. Under such circumstances one must use a method which will continuously record changes taking place in the specimen. Such a method has been developed in connection with a study now

¹ This paper includes the subject matter used in a dissertation submitted to the board of university studies of the Johns Hopkins University in partial fulfillment of the requirements for the degree of doctor of philosophy. A copy of this dissertation is on file at the library of the university.

in progress on the electrical failure of dielectric materials. A description and analysis of this method are presented in the following pages. The method consists essentially in the use of a capacitance bridge in combination with a cathode-ray oscillograph to continuously record the instantaneous current and voltage at the specimen of insulating material under observation in such a way that its power factor is readily computed.

The data obtained with this method consist of continuous records of power factor of the dielectric for individual cycles of alternating stress. Such records may be continued to the point where failure of the specimen occurs, without injury to the apparatus used and without the need for very special precautions for the protection of the apparatus against the surges accompanying the breakdown.

II. THE OSCILLOGRAPH

The recording element of a cathode-ray oscillograph is an electron beam, generated in a high vacuum and deflected by an electric (or magnetic) field. Electrons, emitted by a cathode, are accelerated toward an anode by a suitable voltage and pass through a small diaphragm, usually a hole in the anode itself, to form the beam. The beam strikes a fluorescent screen and gives rise to a luminous spot. The variations in the deflecting field are recorded by photographing the motion of the luminous spot on the screen. In the present case the figures traced on the fluorescent screen are photographed through a viewing window in the side of the oscillograph tube.

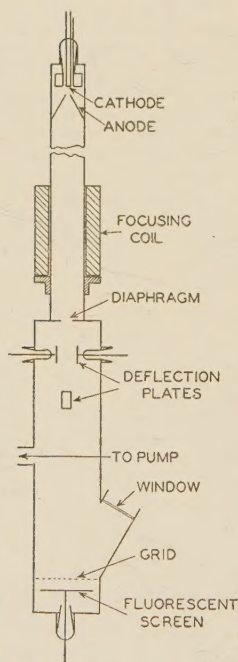


FIGURE 1.—Diagram of oscillograph.

layers of shellac varnish and nitrocellulose brushing lacquer to insure vacuum tightness throughout.

The oscillograph described here is a modification of a design due to Rogowski.² Modifications incorporated in the design make it possible to obtain a continuous record of 60~ phenomena with a maximum sensitivity of 3 mm per volt difference of potential at the deflection plates.

The oscillograph is shown schematically in figure 1.³ It is constructed of drawn-brass tubing with the cathode, deflection plates, and fluorescent screen sealed through glass tubes and introduced into the metal chamber through conical ground joints. Picein wax is used to seal both tapered and soldered joints. The outside of the chamber is coated with alternate

² Rogowski and Grösser; Arch. f. Elektrot., vol. 15, p. 377, 1925.

³ The oscillograph and the camera used with it were constructed in 1927 in the Bureau's instrument shop by J. M. S. Kaufman and E. A. Tibbals who were also responsible for many of the details of design used in the instrument.

The cathode is an oxide-coated filament surrounded by a metal shield which is held at the same potential as the filament. This shield has a plane surface facing the anode and the small hole in its center is almost completely filled by the filament. The cathode system thus is practically a plane surface having a central hot spot which serves as a source of electrons.

The anode is a cone, pointed toward the cathode, with a small hole at its apex through which the electron beam passes. As a result of the focusing action arising from this point-plane arrangement, an intense beam of electrons passes through the hole in the anode and down the tube.

The electron beam is brought to a focus at the fluorescent screen by means of the coil located midway between the anode and the screen. After going through the field of the focusing coil, the beam

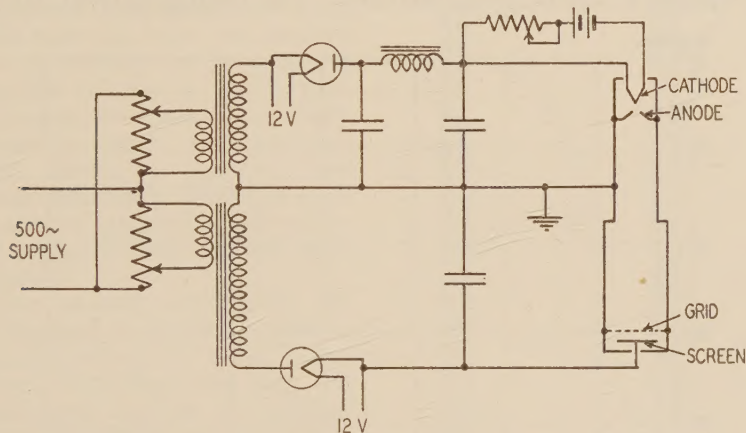


FIGURE 2.—*Voltage supply for oscillograph.*

passes through a diaphragm, between the deflection plates, and through a grid before striking the fluorescent screen.

The fluorescent screen is of finely powdered willemite and calcium tungstate⁴ deposited on a roughened aluminum plate. It is insulated from the metal tube which forms the body of the oscillograph in order that an accelerating potential may be applied between the grid and screen. The grid is formed of no. 40 A.W.G. copper wires spaced 1 mm apart and stretched on a metal frame in electrical contact with the metal tube.

The sensitivity (response for unit stimulus) of a cathode-ray oscillograph in which the electron beam is deflected by an electric field between parallel plates is inversely proportional to the voltage used to accelerate the beam. The brightness of the fluorescence caused by the beam is increased toward a limiting value by increasing the beam voltage. The sensitivity resulting from a low voltage beam can be retained and at the same time the fluorescence can be made sufficiently bright to photograph a single trace of a 60~ wave by ac-

⁴ A number of different fluorescent materials have been tried. Best results have been obtained by using a mixture of calcium tungstate with two kinds of artificial willemite. These materials were prepared and supplied through the courtesy of Prof. R. H. George of Purdue University. The willemites fluoresce green and yellow, respectively, and the calcium tungstate blue. The mixture used shows a brilliant white fluorescence which is very active photographically.

celerating the beam in two stages, the second acceleration being impressed after the beam is deflected and just before it reaches the fluorescent screen.⁵

Direct accelerating voltage is applied between the cathode and the anode and between the grid and the fluorescent screen by rectifying a 500~ voltage and filtering the resulting pulsating unidirectional voltage to minimize the ripple. A diagram of the supply circuit is shown in figure 2.

The oscillograph will operate with a cathode voltage as low as 500 volts. Usually the voltage impressed between the grid and the fluorescent screen is held at 5 kv, since it has been found that little gain in brightness of the fluorescent screen results from increasing the screen voltage above this value.

The brightness of the fluorescent spot as a function of voltage was investigated in the following manner. The heating current through

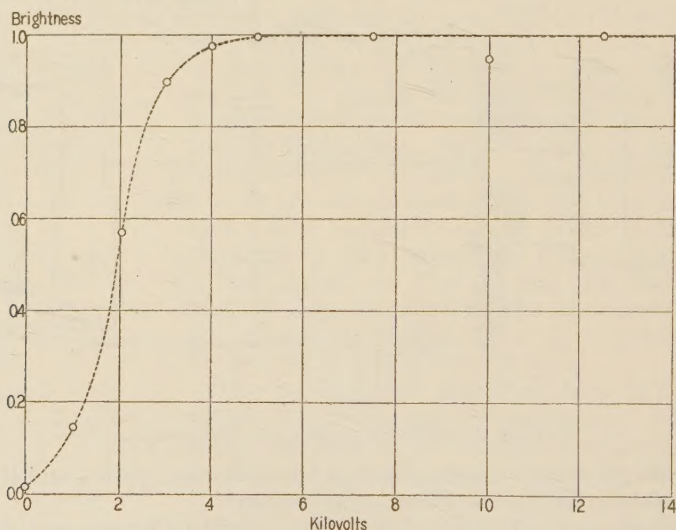


FIGURE 3.—Brightness of fluorescent screen as a function of grid-screen voltage.

the cathode and the voltage between the cathode and anode (500 volts) were held constant. This insured a constant supply of electrons reaching the screen and eliminated any variation in the beam density. The voltage between the grid and the screen was varied and the brightness of the fluorescence was measured by comparing the density of photographs of the spot taken at various voltages. A scale of brightness was set up on the same negative by making a second series of exposures while holding the voltage constant and varying the diaphragm opening of the camera. The density was kept within the scale thus provided by using small diaphragm openings when photographing the spot at high voltages where it becomes very bright. The distance of the camera from the screen and the exposure time were held constant throughout, and an entire series was taken on a single film. This minimized the possibility of density

⁵ This device has been suggested on several occasions: by W. F. G. Swann (1918); W. Rogowski (1920); A. B. Wood (1923). A tube incorporating this feature has been described by E. Sommerfeld, *Arch. f. Elektrot.*, vol. 20, p. 607, 1923.

variation due to unequal development, unequal film sensitivity, and other related causes. The resulting photographs of the spot were then matched in density against the scale provided by the exposures with graded diaphragm openings.

The average values obtained from two such runs are shown in figure 3 plotted to an arbitrary scale.⁶ It is apparent from the figure that no gain is made in the brightness of the fluorescent spot by increasing the voltage beyond 5 kv. This brightness comparison has been made with only the one fluorescent material. It is probable that the voltage at which gain in brightness ceases may vary somewhat with the material used. However, the spot was found sufficiently bright at 5 kv for our purposes when this screen was replaced with the one now in use.⁷

The camera used with the oscillograph is provided with a lens of aperture f:3.5 and takes 35-mm motion-picture film. A continuous motion is imparted to the film through a set of reduction gears operated by a synchronous motor. A friction clutch with a trigger release is incorporated into the driving mechanism so that the motor may be operated continuously and the film set into motion with a minimum of delay. A brake is also provided which operates when the clutch is disengaged and quickly stops the motion of the film. The camera has a magazine holding a 100-foot reel of film, and is so designed that lengths of film up to 20 feet may be exposed and withdrawn. Arrangements are made which permit the extraction of film in full daylight. With the film speed used, continuous records may be made over time intervals up to 45 seconds.

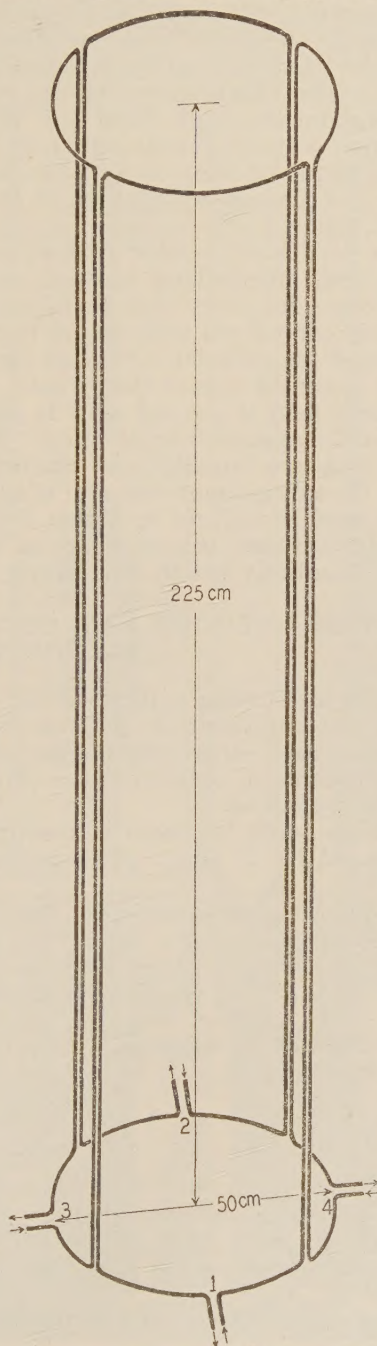


FIGURE 4.—Diagram of coils for compensating the horizontal component of the earth's magnetic field. (Coils 1 and 2 are connected in series to form a pair, coils 3 and 4 form the second pair at right angles. The direction of the current in each coil is indicated by the arrows.)

⁶ The material used for this test was a natural willemite from Franklin, N.J., obtained from Dr. Henry S. Washington.

⁷ See footnote 4, p. 89.

Two pairs of long narrow coils extending the full length of the oscillograph and somewhat beyond, compensate the component of the earth's magnetic field normal to the axis of the oscillograph so that the beam will not be deflected off the screen by the earth's field alone. The two pairs of coils at right angles to each other form a frame about the oscillograph and, by independent adjustment of their currents, permit accurate centering of the beam on the screen. The arrangement of these coils is shown in figure 4. The supporting frame for the coils will be seen at *D* in the photograph of the oscillograph, figure 5.

For the discussion which follows a vertical circular cylinder may be visualized, bounded by the coil pairs and their supporting frame. The long sides of the coils lie in generating elements of this cylinder and the curved coil ends bound right sections of the cylinder. The length of the cylinder is 9 times its radius. For a considerable distance along the axis of the cylinder the horizontal component of the magnetic field of the coil pairs is quite uniform and varies but little for small distances from the axis. Near the ends of the cylinder the field decreases rapidly, but over 0.8 of its length and for distances away the axis not more than 0.1 of its radius the horizontal component of its field is uniform to within 5 percent. The dimensions of the cylinder are such that the path of the electron beam in the oscillograph is entirely within this central zone.⁸

III. THE CATHODE-RAY OSCILLOGRAPH AS A POWER-FACTOR METER

When alternating voltages of the same frequency but differing in phase are impressed on the two pairs of deflection plates at right angles to each other, the fluorescent spot describes an ellipse. The phase difference, α , between the voltages is readily deduced from the area of the ellipse.⁹

Let an x -axis be taken in the direction of one pair of deflection plates (*cd*, fig. 7) and a y -axis in the direction of the other pair (*ab*, fig. 7).

The parametric equations of the ellipse are

$$\begin{aligned} x &= E_1 \cos (\omega t + \alpha) \\ y &= E_2 \cos \omega t \end{aligned} \quad (1)$$

The area of the ellipse is

$$A = \int_{\omega t=0}^{\omega t=2\pi} y dx = \pi E_1 E_2 \sin \alpha \quad (2)$$

Hence, if A , E_1 , and E_2 are measured the phase difference between the voltages can be computed.

If the ellipse is photographed on a film moving at constant speed, p , in the x -direction the parametric equation for x is modified to

$$x = E_1 \cos (\omega t + \alpha) + pt$$

⁸ The analysis leading to this result is too extensive to be presented here appropriately. A solution of the normal field component at the axis of such a cylinder is given by Beyerle; Arch. f. Elektrot., vol. 25, p. 209, 1931. The solution due to Beyerle is not complete but shows the method by which the problem may be attacked.

⁹ Minton; Trans. A.I.E.E., vol. 34, p. 1627, 1915.

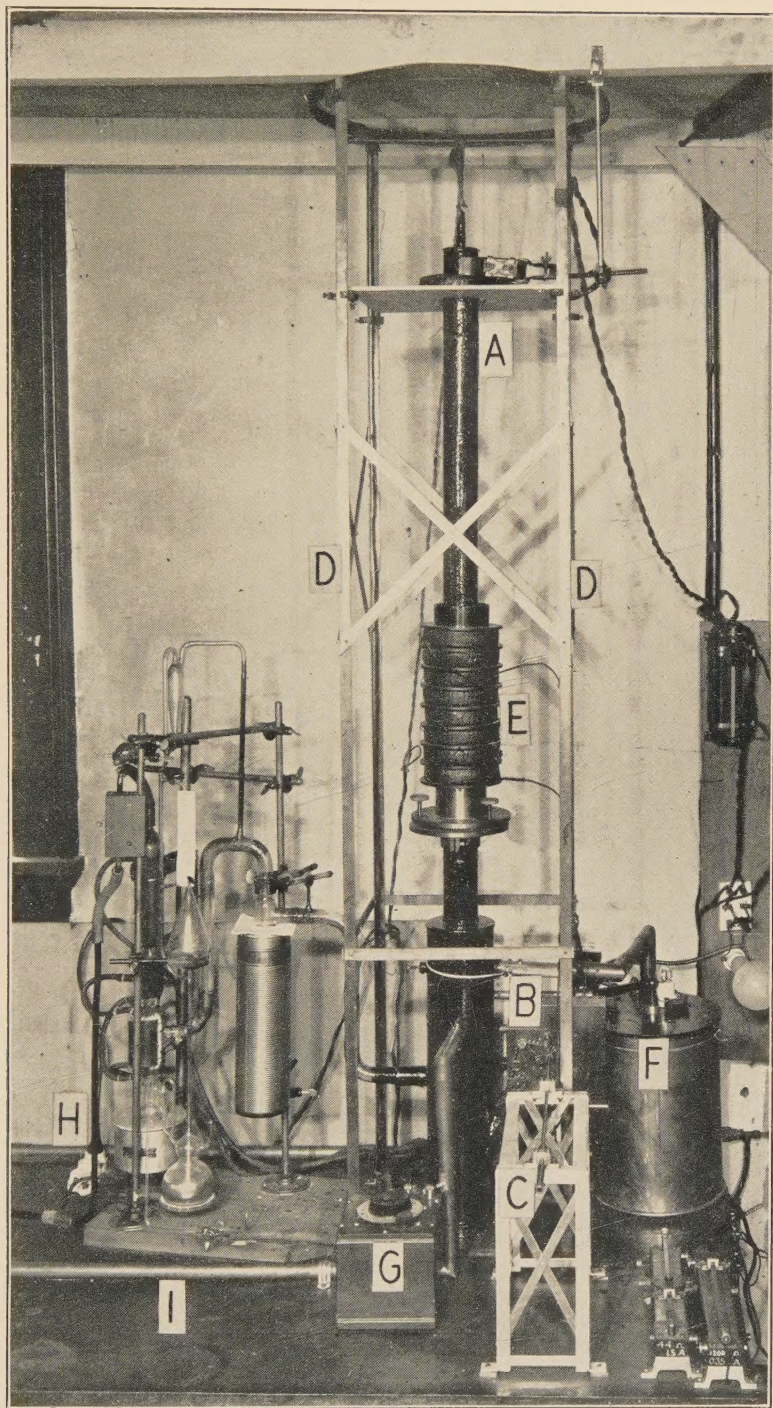


FIGURE 5.—View of oscillograph and auxiliary apparatus.

A, Oscillograph tube; B, camera; C, camera drive shaft; D, frame of compensating coils; E, focusing coil; F, capacitor (C_3 of figure 7); G, capacitor (C_4 of figure 7); H, shielded lead to specimen; I, shielded lead to air capacitor.



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The figure does not now close on itself and successive cycles are separated on the film as shown in the right-hand portion of figure 6. $\sin \alpha$ may still be approximated to a fair degree of accuracy from the

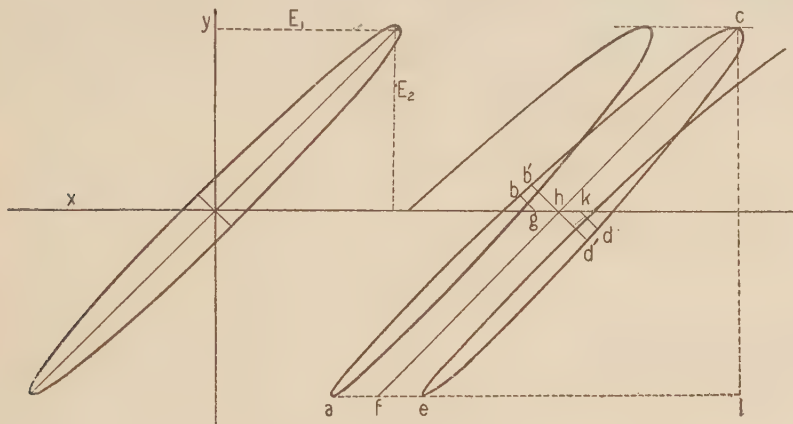


FIGURE 6.—Measurement of power factor from oscillogram.

following considerations: The film advances through a distance ae while a complete cycle is being traced. Starting from a the film has advanced one half of this distance when the tracing point reaches c .

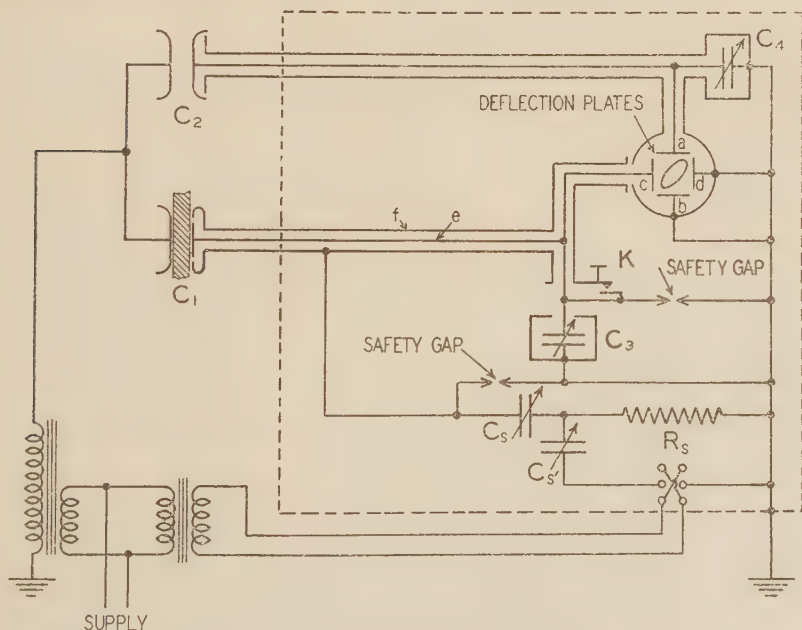


FIGURE 7.—Details of electrical circuit used in measuring power factor.

The points a , c , and e are fixed by the maximum displacements of the trace in the y direction. The x -axis bisects the perpendicular cl dropped from c to the line passing through a and e . The bisection of

ae determines f . The major axis of the ellipse is then approximately given by cf . From the intersection h of cf with the x -axis distances gh and hk along the axis are fixed each equal to one fourth of ae . Now, if the film speed were zero, the points g and k would coincide and the minor axis of the ellipse would be given by the perpendicular to cf intersecting the trace at b and d . The minor axis is therefore approximately given by $(bg + kd)$, where bg and kd are perpendicular to cf . The area of the ellipse

$$A = \frac{\pi}{4} fc(bg + kd)$$

Then since $fl = 2E_1$ and $cl = 2E_2$

$$\sin \alpha = \frac{fc(bg + kd)}{fl \times cl}$$

from equation (2).

It may be noted that

$$bg + kd = b'd' - \frac{ae}{2} \times \frac{cl}{cf}$$

Whence,

$$\sin \alpha = \frac{fc \times b'd'}{fl \times lc} - \frac{ae}{2fl}$$

The latter approximation is used as it reduces the labor involved in obtaining $\sin \alpha$ from an oscillogram.

A somewhat better approximation is possible by an elaboration of the above method if $\sin \alpha$ is large. But its application would be very laborious and it has been found that the accuracy to which the actual lengths can be read from an oscillogram does not justify the added refinement in the method.

The circuit used for the measurement of power factor is shown schematically in figure 7. The capacitor C_1 is the test specimen; C_2 , C_3 , and C_4 are air capacitors. The combination C_2 , C_4 divides the voltage on the circuit, the fractional part $\frac{C_2}{C_2 + C_4}$ being impressed on the deflection plates ab of the oscillograph. The capacitor C_4 is adjustable and the fraction $\frac{C_2}{C_2 + C_4}$ may be varied to change the deflection on the fluorescent screen. Since air is the dielectric in both capacitors, the voltage across the deflection plates ab is in phase with the voltage at the terminals of the supply transformer.

The combination C_1 , C_3 also divides the voltage in substantially the same way, C_3 being adjustable and its value being chosen for convenience so that the voltage across the deflection plates cd is approximately equal to the voltage across ab . Since this voltage divider is made up of an imperfect capacitor and an air capacitor, the voltage across the deflection plates cd is not exactly in phase with either the voltage at the terminals of the transformer or the voltage across the specimen as will be seen in figure 8. It can easily be shown, however, that the phase difference between the voltage across the deflection plates and the voltage at the terminals of the transformer differs by a small and computable amount from the phase defect of the specimen.

The phase-defect angle ϕ_1 of the specimen is defined as the complement of the angle between voltage and current and, for small angles, its value in radians is very nearly equal to the power factor. The air capacitor C_3 may be assumed to have no phase defect. Then the phase difference α (fig. 8) between the voltage across C_3 and that across the terminals of the transformer is given by the expression

$$\tan \alpha = \frac{\frac{1}{C_1} \tan \phi_1}{1/C_1 + 1/C_3} = \left[\frac{C_3}{C_1 + C_3} \right] \tan \phi_1$$

where C_1 is the equivalent series capacitance of the specimen and, since α and ϕ_1 are small,

$$\alpha \approx \phi_1 \left[1 - \frac{C_1}{C_1 + C_3} \right].$$

The angle α is that of the parametric equations (1) for the ellipse which is traced on the fluorescent screen. It differs from the phase defect ϕ_1 of the specimen by the fractional amount

$\frac{C_1}{C_1 + C_3}$. If this fraction is kept small, then $\sin \alpha$ as measured from the oscillogram may be regarded as the power factor of the specimen.

The specimen capacitor shown in figure 7 is equipped with a guard ring and the lead to the oscillograph is shielded. The potential of the shield f is maintained equal to the potential of the lead e from C_1 by means of the guard circuit shown. Adjustment of the shield potential is accomplished by the capacitors C_s and $C_{s'}$. The use of an auxiliary voltage in conjunction with R_s and $C_{s'}$ permits an adjustment for phase in the shield which is practically independent of the magnitude adjustment C_s and, since the auxiliary voltage may be reversed, the phase adjustment is possible whether the guard losses are greater or less than those in C_1 . The figure on the oscillograph screen is itself used to indicate the correctness of the shield potential. To test this potential adjustment, the key K is closed momentarily, connecting the working circuit to its shield. If their potentials are not the same the ellipse on the screen will change its shape when the potentials are brought to equality by the short-circuit. The shield adjustment is correct if there is no shift of the figure when the key is closed.

The effect of a lack of equality between these potentials has been investigated and the analysis is presented in an appendix. It is shown that if the coupling capacitance between the measuring circuit and its shield is sufficiently small when compared to the capacitance in the measuring circuit, the effect of a small lack of adjustment of shield potential is negligible. Hence the measuring circuit is not

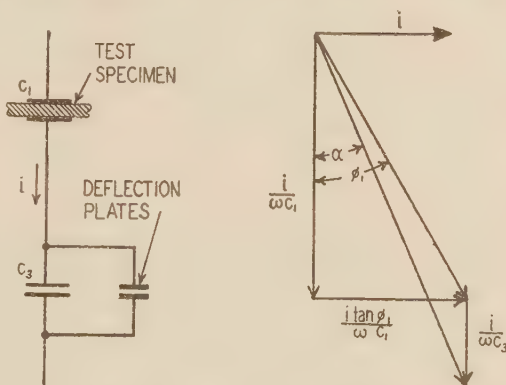


FIGURE 8.—Current and voltage relations in measuring circuit.

The effect of a lack of equality between these potentials has been investigated and the analysis is presented in an appendix. It is shown that if the coupling capacitance between the measuring circuit and its shield is sufficiently small when compared to the capacitance in the measuring circuit, the effect of a small lack of adjustment of shield potential is negligible. Hence the measuring circuit is not

appreciably affected by local disturbances in the guard-ring capacitor even of the specimen is not uniform, and the power factor measured from oscillograms represents the losses in only the part of the specimen that is opposite the central measuring electrode.

IV. TESTS OF THE APPARATUS

Power factors obtained by the method described above have been compared with power factors measured on the same specimens under identical conditions with a Schering bridge. The bridge is of a completely shielded type similar to that described by Kouwenhoven and Baños.¹⁰

Measurements of power factor were made on specimens of varnished cambric and of micanite. The power factor of a sheet of varnished

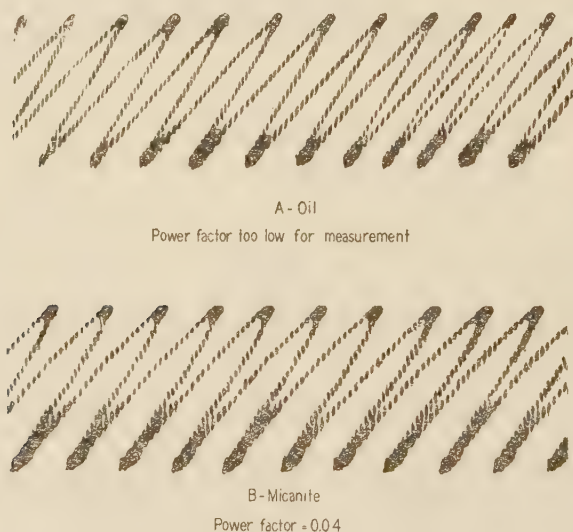


FIGURE 9.—Typical oscillograms taken for low power factor materials.

(Some retouching was necessary on the original oscillograms to improve the contrast in the figure.)

cambric was 0.0835 as measured on the Schering bridge. At the same voltage the power factor read from an oscillogram varied from 0.08 to 0.09 on four separate determinations, the average being 0.087. The power factor of a sheet of micanite was measured on the bridge as 0.033 while under the same conditions the power factor measured from oscillograms ranged from 0.033 to 0.045, the average of eight determinations being 0.039.

Figure 9 shows two oscillograms taken on transformer oil and micanite, respectively. The power factor of oscillogram *A* is too small for measurement. That of *B* is approximately 0.04. The difference in the type of figure is readily seen from inspection.

In order to test the set up at high power factors, sulfonated linseed oil was used as a dielectric. This oil has an abnormally high power

¹⁰ Trans. A.I.E.E., vol. 51, p. 202, 1932. The bridge which was used differs from the one described by Kouwenhoven in the use of a mechanical rectifier and d-c galvanometer as detector. Furthermore, the detector shield is integral with the general shielding of the bridge instead of being connected to a branch point of the bridge itself.

factor at elevated temperatures. Two power-factor readings obtained with the bridge, with oil temperatures of 63 and 61 C and a stress of 100 volts per mil, were, respectively, 0.42 and 0.38. Between these two measurements an oscillogram was obtained at the same stress. This showed a power factor of 0.41. The oil had been heated previously and was cooling during the test.

The data given in the above comparisons are not the result of single measurements from individual cycles on the oscillogram, but are the averages of several readings on successive cycles.

In measuring power factors from the oscillograms the minor axis of the ellipse is the point of greatest uncertainty. When the figure is enlarged to a width of 5 cm, an error of 0.5 mm in the measure-

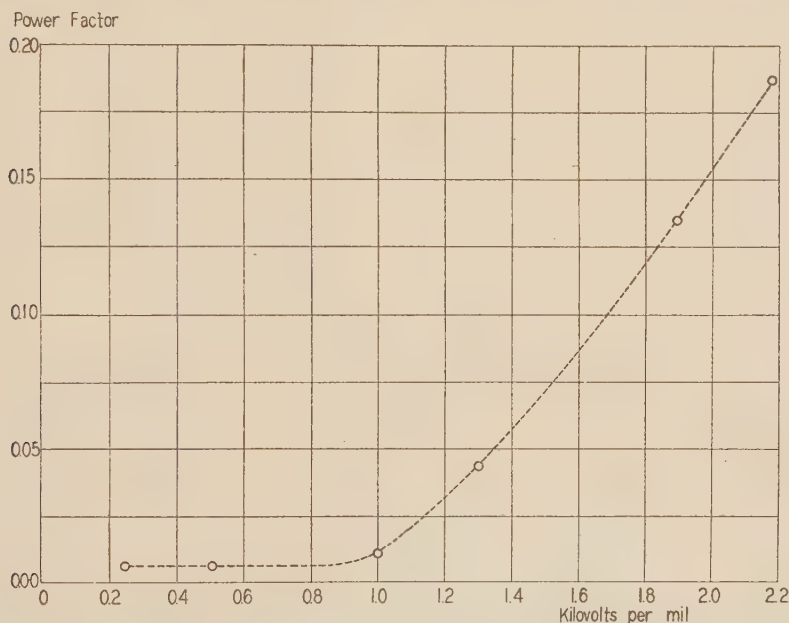


FIGURE 10.—Variation of power factor with voltage for oil-impregnated cable paper. Sample thickness was 5 mils.

ment of the minor axis amounts to about 0.02 in power factor. As errors of this magnitude are to be expected owing to inability to judge accurately the center of the trace on the oscillogram, we cannot hope to detect with certainty a power factor of much less than 0.02 and should expect individual measurements on any oscillogram to have a spread of about this amount.

To further examine the method a continuous record of power factor of a specimen of oil-impregnated cable paper was made with increasing voltage to the point of its electrical failure. The specimen had an area of about 50 cm² and a thickness of about 0.1 mm. It was oven-dried and impregnated in vacuum with oil at a pressure of about 1 mm Hg. After preliminary measurements of power factor at low stress with the Schering bridge, an oscillogram was recorded while the voltage was rapidly increased until the specimen failed. The results are shown in figure 10. The points recorded at 1,000

volts per mil and less represent values obtained with the Schering bridge. (These power factors are too small to read from the oscillogram.) Those above this value were taken from the oscillogram. The last plotted point is an average obtained from measurement on the last 5 cycles preceding breakdown. At this point the power loss in the specimen is of the order of 10 watts.

As a further illustration of the application of the method to the study of the electrical failure of insulation, data are taken from an investigation of this question which is now in progress. Figure 11 shows a cycle-by-cycle record of the power factor in two samples of impregnated 5-mil cable paper during the last second before its breakdown under electrical stress.¹¹ Curve *I* is plotted for a speci-

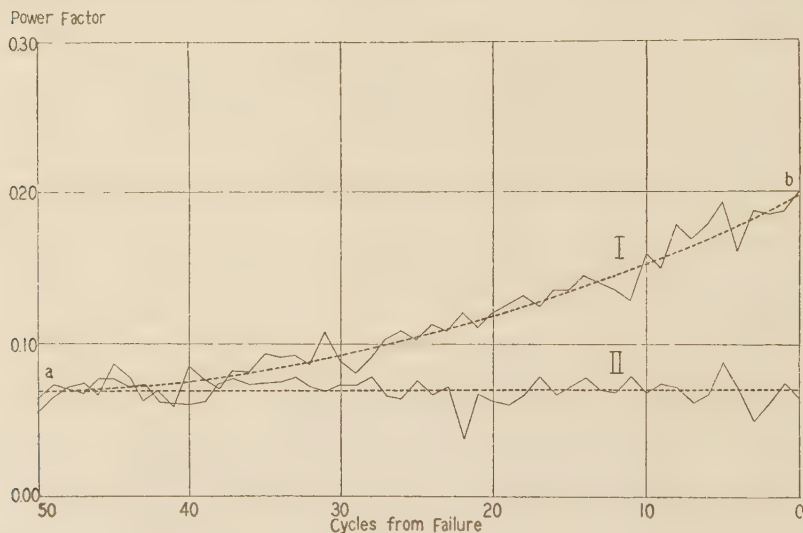


FIGURE 11.—Variation of power factor with time for oil-impregnated cable paper during last second preceding failure.

I. Failure occurred in working area of specimen. II. Failure occurred in guard ring area of specimen. Points connected by full line represent single readings in individual cycles and indicate the precision with which oscillograms may be read.

men which failed in the region covered by the central electrode. (See C_1 of fig. 7.) Curve *II* shows power factor in C_1 when the specimen failed in the guard ring capacitor. The plotted points represent single determinations from individual cycles of alternating stress and clearly show the order of precision with which such measurements can be made. At the point *a* of curve *I* the power loss in the specimen is 0.02 watt and at *b*, 0.1 watt. The central electrode used has an area of about 1 cm² and the capacitance of C_1 is 18 μ f.

It should be noted that the disturbance in the guard circuit caused by approaching failure in the guard-ring capacitor (curve *II*) was not transmitted appreciably to the measuring circuit. This checks the results of the circuit analysis given in the appendix to this paper. The measuring circuit, as shown in the analysis, includes only the area of the specimen covered by the central electrode.

¹¹ This investigation is being carried on jointly with A. E. Peterson, to whom acknowledgment should be made for the use of the data.

V. CONCLUSION

It is apparent from the data given above that, while the method which has been described for measurement of power factor of dielectrics is quite limited as to the precision with which it will measure power factor itself, it is not nearly so restricted in the amounts of power which it will measure. The limit of precision in the measurement of power factor is set by the diameter of the tracing spot and by the size of the ellipse on the fluorescent screen of the oscillograph. The method is, however, well suited to the approximate determination of power factors over very short time intervals and is particularly adapted to the measurement of power factor in extremely small capacitors. At voltages up to 10 kv the ratio of the specimen capacitance to the capacitance shunting the oscillograph plates is of the order of 0.002. If the specimen capacitor were not shielded this ratio could be maintained theoretically for decreasing specimens to a size where the low-voltage capacitance C_3 consisted of the deflection plates alone. As this capacitance is approximately $1\mu\text{f}$ the smallest possible specimen whose power factor could be measured at 10 kv would be $0.002\mu\text{f}$. If, however, the specimen were shielded and equipped with a guard ring a lower limit to size is set by another condition. The limit is now imposed by the coupling capacitance between the measuring circuit and its shield. This capacitance should be not more than 0.1 of the capacitance in the measuring circuit. With the apparatus used the coupling capacitance cannot readily be made less than about $5\mu\text{f}$ which fixes the lower limit of specimen size at $0.1\mu\text{f}$. The minimum power loss which could be detected at 10 kv in such a specimen would be 10^{-4} watt, since the "power-factor precision" should be independent of the specimen size. Actually, a power loss of 0.02 watt has been measured at 10 kv in a specimen of $18\mu\text{f}$ and there is reason to believe that no particular difficulty would be experienced in using specimens a hundredth of this size.

The above figures may be compared to the operating range of a high-sensitivity power-factor bridge. Data given in the description of the bridge due to Kouwenhoven and Baños¹² make such a comparison possible. Kouwenhoven and Baños state that specimens ranging in capacitance from $40\mu\text{f}$ to $1,500\mu\text{f}$ having power factors from 0.00007 to 0.16 have been measured in their bridge at 1.5 kv. Using the minimum values, their bridge can measure power loss of the order of 2×10^{-6} watt at 1.5 kv in a $40\mu\text{f}$ specimen.

It will be seen that, although the precision of the above described oscillographic method for measuring power loss in dielectrics is low, its sensitivity is such that the losses in extremely small specimens can be approximately determined. This should make possible the examination of very minute volumes of an insulating material and the determination of highly localized losses in a nonuniform dielectric.

No limit can be fixed for the maximum specimen capacitance. This is determined solely by the amount of low-loss capacitance available for the capacitor which shunts the deflection plates of the oscillograph.

¹² See footnote 10, p. 96.

be independently adjusted by the variable capacitor C_s . The shield potential E_x should then remain equal to the working potential E_3 when the voltage E_t on the specimen is altered.

If, however, the specimen of insulation under examination is not uniform, losses may not increase at the same rate in the working capacitor C_1 and in the guard-ring capacitor C_g , particularly in the region of instability which precedes the failure of the specimen. When this occurs the potentials of the working circuit and of the shield will no longer be equal and the capacitance between them will tend either to feed current into the measuring circuit or draw it off, depending on the direction of the potential inequality. It is, therefore, necessary to consider the interaction between the measuring circuit and its shield caused by their capacitive coupling.

The network to be considered is shown in figure 12. The following vector relations are apparent:

$$E_x = \rho E_t \quad (1)$$

ρ being a complex quantity which takes into account the ratio of E_x and E_t and also their phase relation.

$$E_3 = \frac{I_3}{j\omega C_3} \quad (2)$$

where C_3 includes the capacitance of the oscillograph plates.

$$I_x = (E_x - E_3)j\omega C_x \quad (3)$$

$$I_1 = (E_t - E_3)j\omega\gamma C_1 \quad (4)$$

where $\gamma = \cos \phi_1 (\cos \phi_1 - j \sin \phi_1)$; ϕ_1 being the phase defect of C_1 . Here C_1 is the equivalent series capacitance of the specimen.

$$\begin{aligned} I_3 &= I_1 + I_x \\ &= (E_x - E_3)j\omega C_x + (E_t - E_3)j\omega\gamma C_1 \end{aligned} \quad (5)$$

From (2) and (5) we have

$$E_3 = \frac{1}{j\omega C_3} [(E_x - E_3)j\omega C_x + (E_t - E_3)j\omega\gamma C_1]$$

whence

$$\begin{aligned} E_3 \left(1 + \frac{C_x}{C_3} + \gamma \frac{C_1}{C_3} \right) &= \frac{1}{C_3} [E_x C_x + \gamma E_t C_1] \\ &= \frac{E_t}{C_3} [\gamma C_1 + \rho C_x] \end{aligned}$$

or

$$\frac{E_3}{E_t} = \frac{\gamma C_1 + \rho C_x}{C_3 + C_x + \gamma C_1} \quad (6)$$

and

$$\frac{E_3}{E_x} = \frac{E_3}{\rho E_t} = \frac{\frac{\gamma C_1}{\rho} + C_x}{C_3 + C_x + \gamma C_1} \quad (7)$$

Now let $\frac{E_3}{E_x} = 1 + k$ where k is the fractional departure of the shield potential from that of the working circuit.

Then from (7)

$$1 + k = \frac{\frac{\gamma C_1}{\rho} + C_x}{C_3 + C_x + \gamma C_1}$$

and

$$\rho = \frac{\gamma C_1}{C_3 + \gamma C_1 + k(C_3 + C_x + \gamma C_1)} \quad (8)$$

Substituting (8) in (6)

$$\begin{aligned} \frac{E_3}{E_t} &= \frac{\gamma C_1 \left[1 + \frac{C_x}{C_3 + \gamma C_1 + k(C_3 + C_x + \gamma C_1)} \right]}{C_3 + C_x + \gamma C_1} \\ &= \frac{\frac{\gamma C_1}{C_3 + \gamma C_1} \left[1 + \frac{C_x}{C_3 + \gamma C_1} \left(\frac{1}{1 + k \left(1 + \frac{C_x}{C_3 + \gamma C_1} \right)} \right) \right]}{1 + \frac{C_x}{C_3 + \gamma C_1}} \\ &= \frac{\gamma C_1}{C_3 + \gamma C_1} \left[1 - k \frac{C_x}{C_3 + \gamma C_1} \left\{ 1 - k \left(1 + \frac{C_x}{C_3 + \gamma C_1} \right) + k^2 \left(1 + \frac{C_x}{C_3 + \gamma C_1} \right)^2 \right\} \right] \end{aligned}$$

The voltage division to be expected in the measuring circuit if the shield potential is correct is

$$\frac{E_3}{E_t} = \frac{\gamma C_1}{C_3 + \gamma C_1}$$

If the shield potential is unbalanced by a fractional amount, k , then the measuring circuit is changed (to a first approximation) by a fraction $k \frac{C_x}{C_3 + \gamma C_1}$. This will be negligible if $\frac{C_x}{C_3 + \gamma C_1}$ is kept small. In the apparatus used this ratio is less than 0.04 and it is believed that the power factor measured for the specimen C_1 is quite independent of local disturbances in the part of the specimen which forms the dielectric of the guard-ring capacitor C_g .

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BIOGRAPHICAL SKETCH

Forest Klaire Harris was born August 26, 1902, in Gibson County, Indiana. He received his preparatory education in the public schools of Weatherford, Oklahoma, and in the Southwestern State Teachers College. He entered the College of Arts and Sciences of the University of Oklahoma and received from it the degree B. A. in 1921, and the degree M. S. in Physics in 1923. He has been employed at the U. S. Bureau of Standards continuously since that time, first as a Research Associate of the Munsell Color Company and later as a member of the scientific staff of the Bureau of Standards. He has attended graduate courses given at the Bureau of Standards by Drs. Snow, Heyl and Curtis. He entered the Johns Hopkins University in 1928 as a candidate for the degree of Doctor of Philosophy. His work at the Johns Hopkins University has included lecture courses under Professors Wood and Herzfeld and Drs. Bearden and Dieke of the Department of Physics; Professors Murnaghan and Cohen of the Department of Mathematics; and Professor Kouenhoven of the Department of Electrical Engineering.

